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RESEARCH PROGRAM ON THE ORGANIZATION AND MANAGEMENT OF RESEARCH AND DEVELOPMENT

# The Analysis of Large Scale R&D Programs: A Case Study of Project Mercury

Archie L. Wood

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This working paper is the first in a series of reports on studies of New Approaches to Program Management, under the general direction of Professor Edward B. Roberts. Other publications of this series now being prepared include additional case study analyses of space programs and an investigation of the effectiveness of incentive contracts in research and development. These research undertakings have all been supported by grant NaNsG 235-62 of the National Aeronautics and Space Administration to the M.I.T. Sloan School of Management.

## ABSTRACT

This paper is the first of a planned series of analyses of large-scale research and development programs. The objectives of this study are threefold:

(1) to develop better understanding of the principal causes of program results in large-scale technological undertakings;

(2) to create new analytic and predictive tools for assessing the future course of programs planned and in-process;

(3) to attempt application of these new approaches to a set of on-going programs, both as a test of the methods and as a possible source of contribuion to program effectiveness.

In carrying out these analyses major projects of the United States space flight program have been selected for individual and comparative case study. The results of the initial phase of this research are described in this paper. It describes a case study of Project Mercury, the United States' first manned space flight venture. The paper attempts:

(1) to document authoritatively but concisely, from a program management viewpoint, the technical, schedule, and financial results of Project Mercury;

(2) to trace the project's evolution from its inception in 1958 through its completion in 1963;

(3) to draw from analysis of these data descriptions of the underlying policies and processes by which the project was conducted;

(4) to utilize these data and descriptions as contributors to the overall purposes of the study, as outlined above, broadly the development of new approaches for program management.

The research documented in this paper confirms the popularly-held view of the technical success of Project Mercury. It also concludes that the project was restricted to its original objectives, but that the perceived cost went from an original budget of about $200 million to a final actual cost of $384.1 million. Furthermore, the first manned Mercury flight was 22 months later than initially scheduled and the entire project duration was about 30 months longer than scheduled. The research further concludes that these results of Project Mercury are consistent with those of earlier programs similar in size and technological character, but sponsored by the various United States military services.

This paper draws inferences that:

(1) a tendency (no doubt a necessary one) to decide nearly all issues with astronaut safety as a paramount criterion contributed to the cost growth and schedule slippage;

(2) factors such as a very short design schedule and the heterogeneity of pertinent technologies resulted in a relatively inferior systems engineering job on the space capsule itself;

(3) the capsule systems engineering problems resulted in subsequent slippages and additional costs due to resultant difficulties in flight preparation;

(4) other factors contributing to cost growth and schedule slippage were (a) a lack of system and program definition at the program outset, and (b) technological risk due primarily to system unreliability.

# CASE STUDY OF PROJECT MERCURY

## Background

Project Mercury was the first program carried out by the United States to put man in space. The program was conducted by the National Aeronautics and Space Administration, and was initiated in late 1958, just after the establishment of N.A.S.A. By early 1959 N.A.S.A. had let the contract for the manned satellite capsule; by the summer of 1959, proposals were in N.A.S.A.'s hands for the tracking network. These were the two largest developmental elements of the program.

The program was planned to use existing boosters--Redstone, Jupiter and Atlas.

As is well known, the program was highly successful, resulting in six successful manned space flights ranging from Redstone flights of a few minutes to a final one-day orbital flight.

There are aspects of the Mercury Project, however, that need analysis for the inferences that can be drawn for use in the future. Such questions as the following present themselves: What were the stated objectives and the real objectives of Project Mercury? Was the Mercury Program carried out on schedule? If not, why? Was the program executed within the projected budget? If not, why? What was the "risk" content of Project Mercury? Did the expectations of problems materialize? What was the program content in terms of objectives? Were these contents realized by the program as executed? If not, what were the underlying reasons? If the problems experienced fell short of expectations, what might the program have cost if these expectations had been realized?

This study, conducted solely from printed matter available in the public

domain, is an attempt to answer some of these questions and to draw some of the inferences that might be useful in the future.

## Planned and Accomplished Objectives

The announced objectives as of late 1959 of Project Mercury were three:

1. To place a manned space capsule in orbital flight around the earth;
2. To investigate man's performance capabilities and ability to survive in a true space environment;
3. To recover the capsule and the man safely.[1]

## Technical Requirements of Project Mercury and the State of Existing Technology

The Mercury mission to achieve these objectives can be divided into seven "phases". Each phase contains some of the primary technical requirements imposed by the mission objectives and by the environment. The phases are shown schematically in Figure 1 on the next page. Each of the phases of Figure 1 can be further broken down into individual functions to be performed; however, analysis of even so simplified a representation as that above permits an overall comparison of the state of existing technology in late 1958 with Mercury requirements.

Launch Preparation. This mission phase is simply the countdown. In Mercury it presented few problems not already met and solved in the many missile countdowns conducted by both NASA and the military by late 1958. The

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[1]Superscripts refer to footnotes listed at the end of this paper.

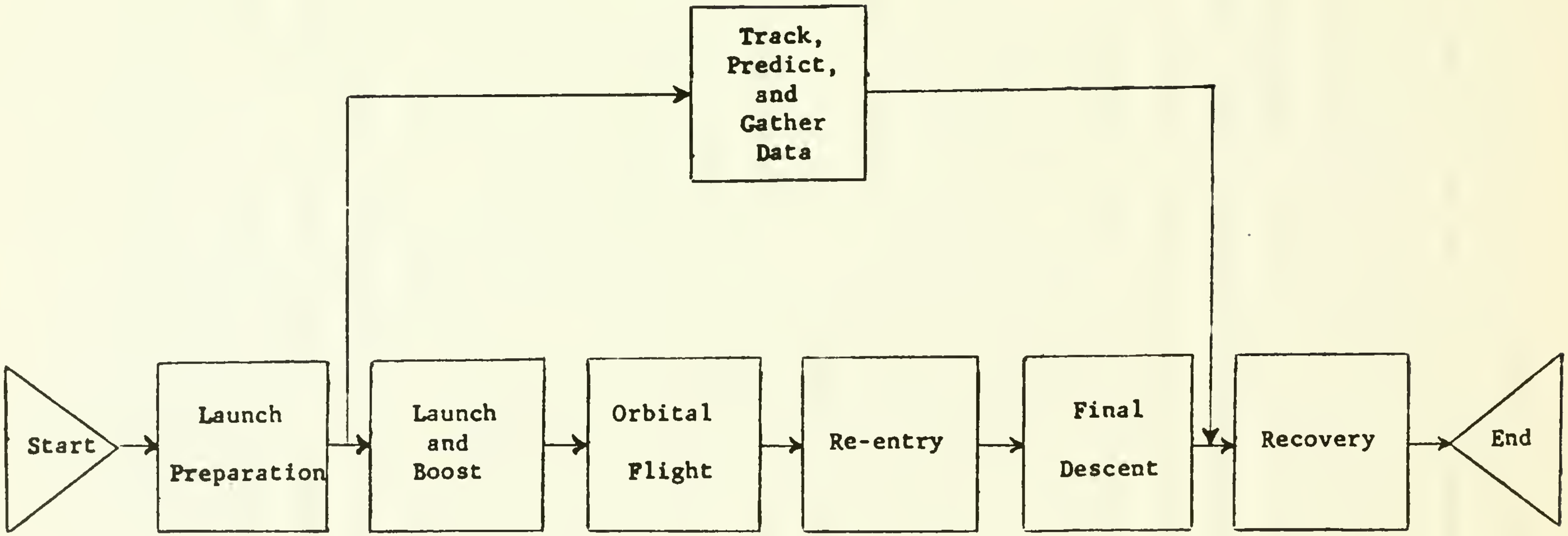



**FIGURE 1**

**The Gross Phases of the Mercury Mission**

presence of the astronaut did not modify the countdown in any particularly unusual way other than for the safety requirements his presence imposed. Obviously new psychological pressures were felt due to concern for his safety. No requirements for launch at a predicted time existed.

Launch and Boost. The launch and boost phase of the Mercury mission was of course a complex process requiring guidance and control, propulsion, and almost an infinity of other detailed functions. Each of these had been carried out previously, however, with existing ballistic missiles, in particular, Atlas, Thor, Jupiter, and Redstone, to name the most obvious examples. Redstone had orbited objects by late 1958 and the Atlas had flown some 6300 miles in tests at Cape Canaveral.[2] At that time Atlas had been in flight test for about 18 months[3] and Redstone for about 5 years.[4] It would appear that other than for reliability and safety a straightforward adaptation of one or more of these vehicles to the Mercury Project would meet Mercury needs.

The problem of safety and realiability, two tightly interwoven requirements, are discussed separately below. However, since escape during launch is an integral part of the launch phase it is discussed here.

Safety during launch consisted primarily of extracting the astronaut from the launch vehicle in event of a launch vehicle abort. This required first a system to sense the presence of an incipient or actual aborted mission and, second, a means of removing the astronaut, separately, or capsule and all, from the vicinity of the launch vehicle. Although these requirements had not been met before, their satisfaction was straightforward and certainly no new technology was required. The tractor rockets on the capsule escape tower and the abort sensing and implementation system were designed to satisfy these needs.

In short, launch technology had developed sufficiently by late 1958 that high confidence in the ability to launch the Mercury capsule into orbit was warranted. Little if any new development was required since existing boosters could be adapted to the purpose. The main area of reasonable concern was booster reliability.

Orbital Flight. The orbital phase of the Mercury mission imposed few new requirements and none that had not been met at least partially by other previously developed equipment. Among these requirements were:

1. Protection from the hard vacuum of space;
2. Protection from radiation;
3. Protection from micro-meteorite impact;
4. Provision of life support in the form of environmental control, breathing gases, and waste disposal (or storage);
5. Support and protection of the astronaut during exist and re-entry accelerations;
6. Attitude control capability;
7. Sufficient automatic controls and/or command capability to permit recovery even if the astronaut were incapacitated;
8. Systems to initiate departure from orbit, i.e., controls, instruments, and retro-rockets.

The functional needs of the orbital phase had been satisfied at least partially in existing systems. A complicating factor, however, was weightlessness, a new environmental element. High altitude high performance aircraft then in operation contained systems embodying most of the technology of the life support system required as well as cockpits capable of maintaining reasonable environments even in the extreme upper reaches of the atmosphere. Radiation protection and micrometeorite protection appear to have been considered relatively insig-

nificant problems since no treatment of these hazards is present in literature surveyed for this study.

Attitude control systems using thrusters (reaction controls) were being built in late 1958 in the X-15 and installed experimentally in F-104's for certain flight tests. NASA was flying an "iron cross" using thrusters for controls.

The iron cross was a rigidly constructed cross configured device mounted on a gimbal near its center of gravity. Also on the cross was a rudimentary cockpit and a reaction control system. A pilot could fly the device from the cockpit, and since the device's response to an application of thrust at one of its extremities was an angular acceleration, it simulated the dynamics of attitude control of a spacecraft.

Instruments for attitude control and initiating departure from orbit were either available or were easily designed using existing technology.

Support of the astronaut during high accelerations was shown to be feasible in July 1958 through use of contour couches.[5]

Perhaps the major challenge of the space capsule was the systems engineering job of reliably meeting all imposed requirements in a high performance spacecraft and integrating this craft with the launch vehicles, ground equipment, and maintenance and test equipment. Clearly many technological disciplines were involved and many varieties of equipment were required in the capsule. This, no doubt, complicated the system engineering job further.

Re-entry. The re-entry phase was probably the phase about which least was known. However, the ballistic missile programs had by late 1958 flown both ablative and heatsink re-entry vehicles successfully. The U.S. Army had recovered an ablative re-entry vehicle flown in late 1957.[6] Also by late 1958 the Air Force had conducted the X-17 re-entry test program and had under-

way other pertinent programs. NASA chose to carry out two technical approaches to the heat shield, ablative and heat sink. The former was flown in September 1959 and the test was highly successful.[7] With this success all thought of using any type but an ablative heat shield was abandoned.

Final Descent. The final descent was to have been made with parachutes into water. The system consisted of a small drag parachute to stabilize and slow the capsule at speeds below Mach 1.5 and at altitudes below 70,000 feet. The main parachute was to open at about 10,000 feet for the final descent. The development of such systems in late 1958 left little doubt that anything more than engineering was required to qualify necessary equipment. Such qualification was achieved in the summer of 1959.[8]

Recovery. The recovery phase (excluding impact prediction) of a Mercury mission did not present requirements of any significant technological consequence. The task was mainly one of proper employment of sufficient recovery forces and use of standard equipment adapted to the specific task at hand.

Tracking, Trajectory Prediction, Command and Instrumentation.[9] It was obvious early in the Mercury Project that a complex world-wide tracking network would be required to insure adequate flight safety. Study of these needs resulted in the definition of a far flung network possessing remarkable qualities of speed, reliability and accuracy.

This network ultimately contained, among others, the following equipment:

16 tracking radars
16 telemetry receiving stations
16 air to ground voice radio stations
3 IBM 7090 Computers
1 IBM 709 Computer
1 Burroughs/General Electric Computer
102,000 miles of teletype lines
60,000 miles of telephone lines
15,000 miles of high speed data lines
A complete mission control center

Nearly all of this equipment was of standard commercial or military varieties, some with varying degrees of modification. Some new equipment (for example, acquisition aids for the radars and digital interface coupling equipment) had to be built but none of this required significant technological advances. The network did present a very substantial integration task; fortunately, this network was largely a system unto itself with only procedural interfaces or instrumentation interfaces with the rest of the Mercury equipment. Also, it contained largely the technologies of a narrow range of disciplines--electronics and communication system engineering.

Technical Challenges of Project Mercury. Given that little if any new technology was required what were the technical challenges of Mercury? There would appear to be three:

Astronaut Safety. Safety was a paramout issue in every critical subsystem of Mercury. Statements of related policy are cited later in this paper. The reader should distinquish between safety and reliability. In an oversimplified form the probability of losing an astronaut can be thought of as $P_L = P_F \times P_{FE}$; or, the loss probability equals the probability of catastrophic failure times probability of failure of escape systems.

System Engineering and System Integration. Two outstanding examples of these system-requirements are the spacecraft (and its launch vehicles) and the tracking network. Both of these presented very complex conglomerations that had to be engineered into finely tuned systems.

Reliability. Reliability was at the outset recognized as a problem. As is cited in this paper, even with the strenuous efforts exercised by the Mercury development program (for good coverage of this see NASA SP-45, Chapter 6), significant numbers of component and subsystem failure still occurred in Mercury flights.

## The Flight Test Program

The manned flight program consisted of six flights summarized in the table below:

Table 1. Manned Flight Program

| | | | | | |
|---|---|---|---|---|---|
| Mercury Redstone | 3 | May 5, 1961 | Shepard | suborbital | 15 min. + |
| Mercury Redstone | 4 | July 21, 1961 | Grissom | suborbital | 15 min. + |
| Mercury Atlas | 6 | Feb. 20, 1963 | Glenn | 3 orbits | 5 hours |
| Mercury Atlas | 7 | May 24, 1962 | Carpenter | 3 orbits | 5 hours |
| Mercury Atlas | 8 | October 3, 1962 | Schirra | 6 orbits | 9 hours |
| Mercury Atlas | 9 | May 15 & 16 1963 | Cooper | 22 orbits | 34 hours |

Even though serious consideration was given to flying both additional 3 orbit flights and additional 1-day flights[10], the Mercury program was ended with the manned flight program summarized above. As is well known, recovery was completely successful in every manned flight except that of MR-4, in which the capsule was lost in the sea.

The flights were punctuated with minor difficulties (some of which seemed quite serious at the time) that were effectively coped with by the astronauts or by ground crews. The seriousness of many of these failures was minimized by redundancy or other provisions for failure made in the system design. The _Mercury Project Summary_, NASA SP-45, points out an average of ten spacecraft component malfunctions or failures per manned flight despite intensive efforts to discover and correct all anomalies prior to flight. In none of these, however (even though some of these failures were critical), did mission failure result. In every case redundancy or pilot back-up modes were effective. (See page 110, NASA SP-45).

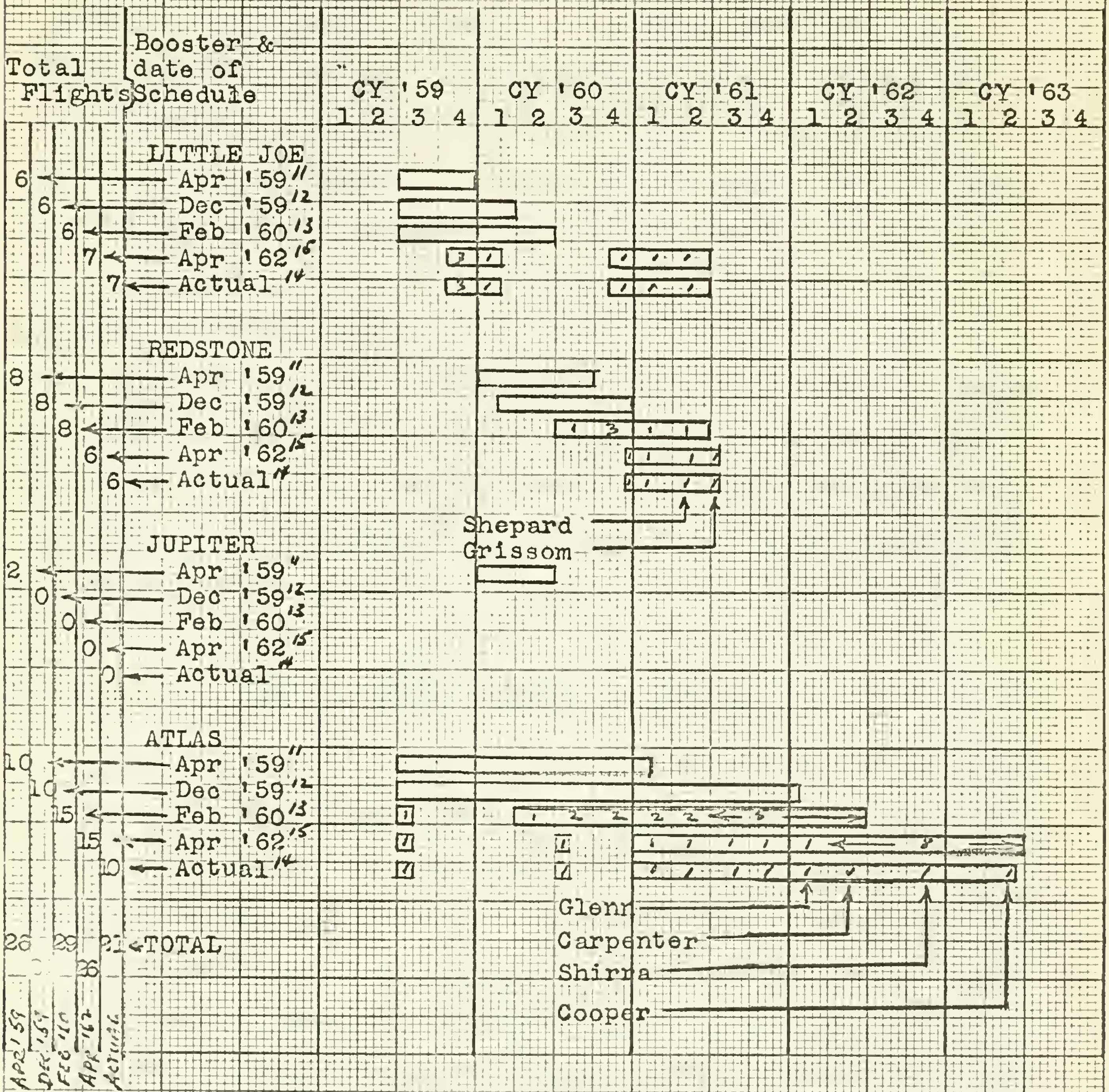
Looking at the results of the flights and the restricted number of flights and noticing that only two can be considered as near duplicates of any other flight, one would conclude that:

a. project objectives were realized;

b. the project was essentially restricted to its original objectives.

FIGURE 2

Mercury Flight Test Planning and Actual Flight Test Program



Programmed Flights versus Accomplished Flights. At different times in its evolution, Project Mercury was planned to contain various numbers of flights. Specifically, the planned flight programs at various times are summarized in Figure 2. Examination of the total flights at the left of the figure reveals that the program as accomplished contained one extra Little Joe flight, two less Redstone flights, and two less Jupiter flights than the original program. The Jupiter flights were not planned to be manned.[11] Each of the astronauts rode one flight. (This statement excludes the astronaut who was disqualified for physical reasons.)

Summary of Content Discussion

Project Mercury achieve the objectives it set out to achieve. It apparently was not expanded to encompass other objectives and the program flew very close to the number of flights planned at the outset. The program can be said to have adhered very closely in actual conduct to the original objectives and program content.

## Project Mercury's Adherence to Schedule

Figures 3 and 4 show how Project Mercury fared as regards its adherence to schedule. Figure 3 shows reference line representations of the planning in early 1959 and of the actual conduct of the program. It can be seen that the first developmental flight was about one month late. This increased to about three months which, when added to spacecraft delivery slippage, placed the flight test corresponding to the 8th originally planned test about 10 months behind schedule. Additional slippage accrued such that by the flight test corresponding to the 18th originally planned test, a slip of about 14 months existed. Additional slippage accrued then of about 8 months, putting the first manned orbital flight some 21 or 22 months late.[17]

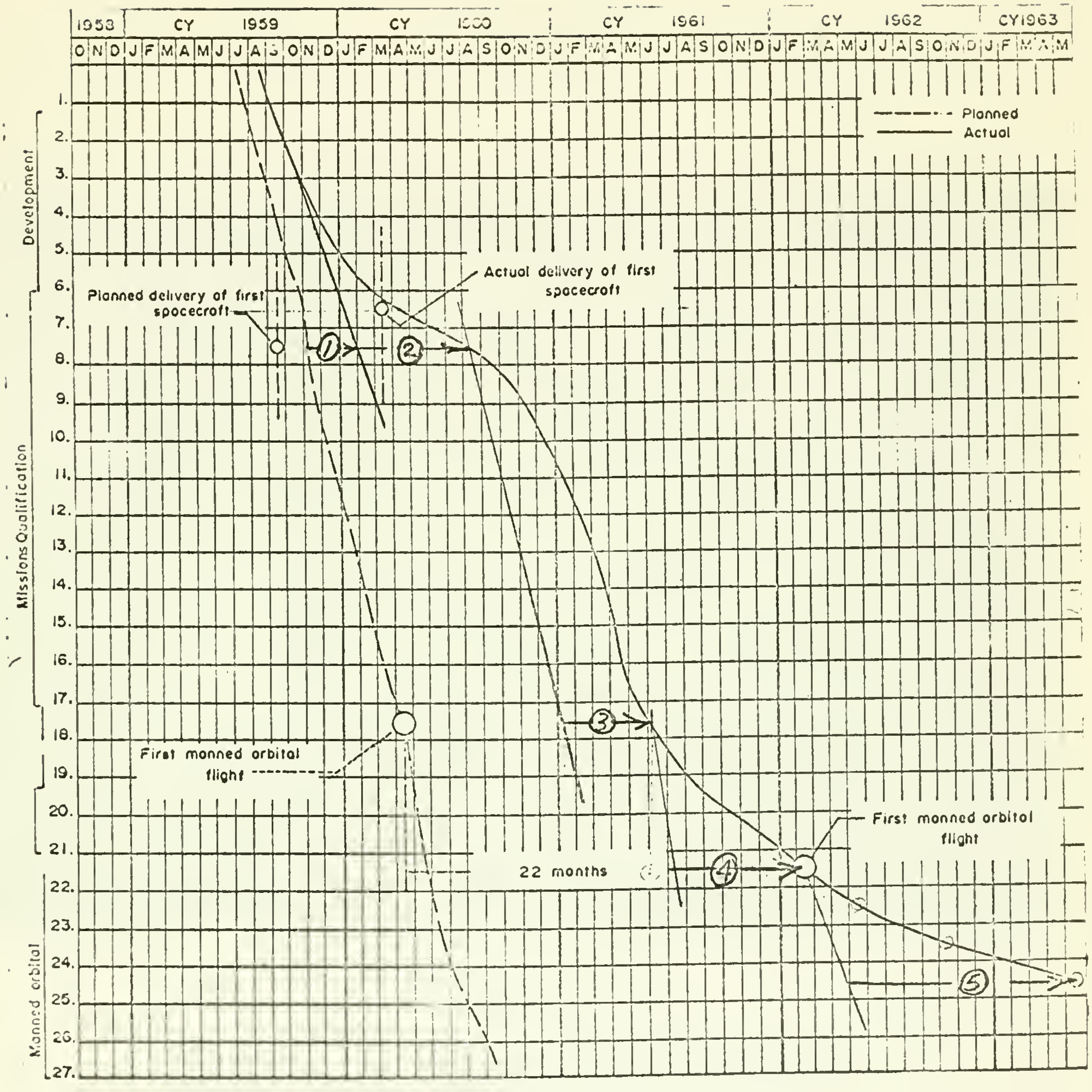



FIGURE 3

COMPARISON OF PLANNED AND ACTUAL FLIGHT SCHEDULES

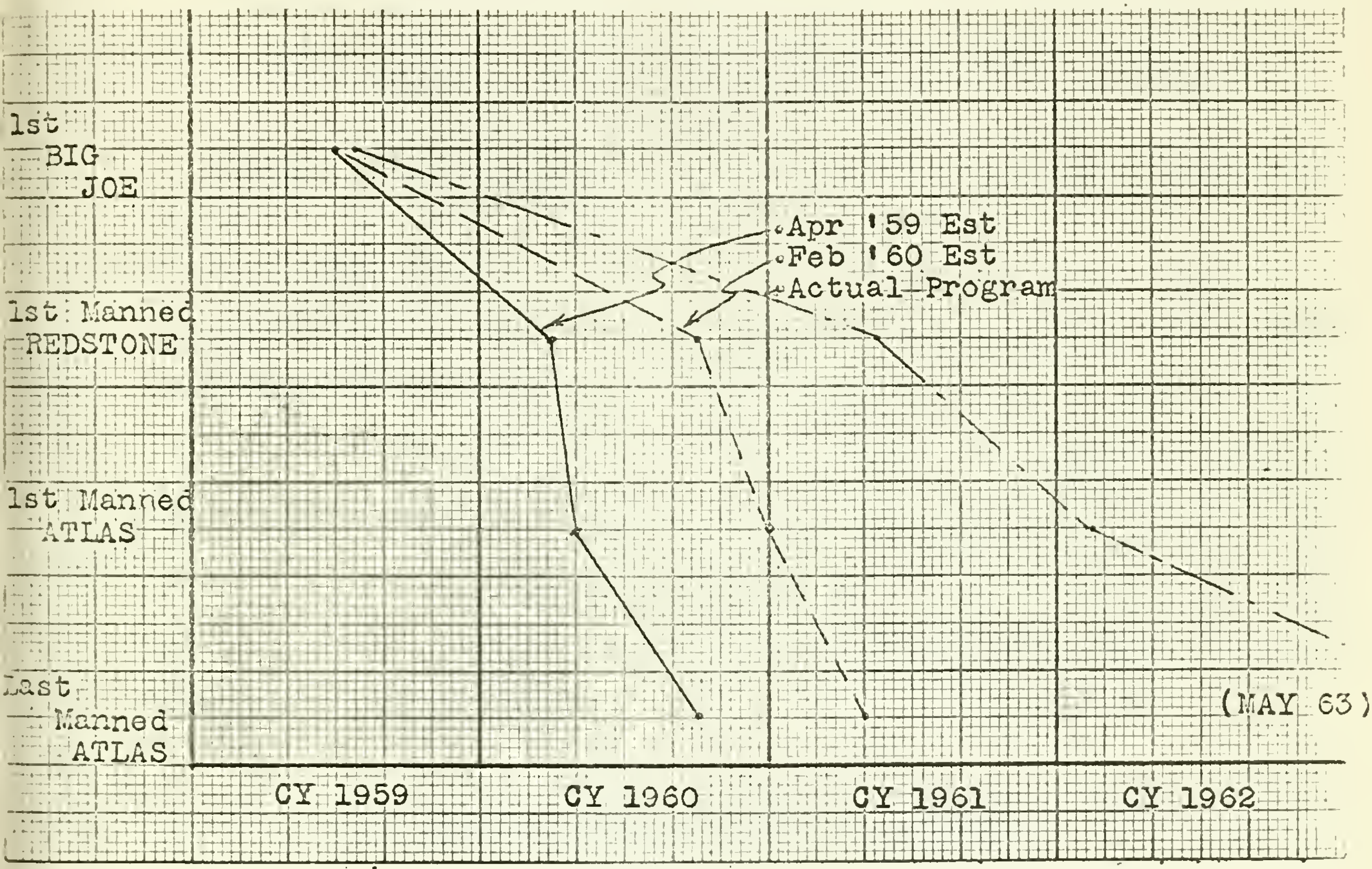



FIGURE 4

Comparison of Schedules, PROJECT MERCURY

A much oversimplified analysis of these slippages is as follows:

Slip 1--amount, 3 months; probable causes, difficulties in preparation for flight plus flight failures of Little Joe boosted flights plus about one month of design and/or fabrication slippage that had developed prior to the first developmental flight.
Slip 2--amount, 6 months; probable causes, difficulties in design and fabrication of spacecraft leading to spacecraft delivery slippage.
Slip 3--amount, 5 months; probable causes, longer launch preparation times* than estimated, accumulated over about 11 flights.
Slip 4--amount, 8 months; probable causes, structural and guidance failures in Atlas boosted launches plus longer launch preparation times than estimated.
Slip 5--amount, 12 months; probable causes, an accumulation of longer launch preparation times due to original underestimates.

Total slippage--about 34 months.[18]

A slightly different and more approximate way of looking at the schedule performance of Project Mercury is shown in Figure 4. This figure is drawn from Figure 2 previously presented. This shows an intermediate schedule line that reflects probably, slips 1 and 2 above since these had materialized by early 1960 when the intermediate estimate was made. The intermediate line does not reflect the Atlas failures nor the longer preparation times actually encountered at Cape Kennedy.

## Project Mercury's Adherence to Budget

To discuss the budget it is first necessary to establish just what the program at various points in time intended to achieve. The objectives of the Project Mercury are reasonably clear and are stated above. Perhaps the main item of controversy is whether or not the 1-day missions were included in the program and therefore in the budgets. There is ample evidence, indicated below, that indeed the 1-day mission was included up until October 1959.

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*"Launch preparation times" as used here is that time required to modify, test and assemble the spacecraft and launch vehicle as well as the actual countdown.

"Manned Space Flight is N.A.S.A.'s top priority program. Increased costs have resulted from program complexities not foreseeable at the time the fiscal year 1960 budget was drawn up. The program as justified contained funds for work on the extension of man's space flight capability beyond Mercury; in order to make these funds available to Mercury, all such advanced work has been delayed for a year and the 18 orbit missions have been reduced to a 3 orbit mission. An additional $7.515 million has to be programmed to maintain the Mercury rate of progress..."[19]

Dr. Abe Silverstein of N.A.S.A. is quoted in Aviation Week of June 29, 1959, as saying that the capsule might be allowed to go approximately 18 circuits, which would extend the orbital time to somewhat over 24 hours, and that provisions for the astronaut had been made for at least that time period in the Mercury capsule.[20]

In the November 24, 1958 issue of Aviation Week, the projected Mercury capsule is described rather accurately. This description is stated in the article to be based on the Request for Proposals then in industry's hands for this capsule. Among other attributes said to be required of the capsule was an 18 orbit capability.[21]

It would appear then that budget estimates made for Project Mercury prior to October 1959 included the 1-day mission and those made subsequent to that time excluded it. Some of the key program budget estimates and the date on which these estimates were made are shown in Table 2. All these have been adjusted to include the one day mission.

Table 2.

Program Cost Estimates--Project Mercury

| | | |
|---|---|---|
| February | 1959 | $200,000,000[22] |
| November | 1959 | $346,000,000[23] |
| March | 1962 | $351,500,000[24] |
| March | 1963 | $347,000,000[25] |
| May | 1963 | $384,100,000[26] |

Before drawing direct comparisons of the figures in Table 2 the reader should look carefully at the program sizes set forth in Figure 2. As can be seen, the program estimates are associated with substantially different numbers of flights. Table 3 below presents data from Figure 1 and Table 2 in slightly different form:

Table 3

Mercury Program Comparisons

| Program | Cape Kennedy Flights* | Approximate Program Duration | Duration of Cape K. Operations** | Budget |
|---|---|---|---|---|
| April 1959 | 20-8 MR,2MJ,10MA | 2 years | Approx. 20 mo. | $200,000,000 |
| Feb. 1960 | 23-8 MR, 15 MA | 2½ years | Approx. 28 mo. | $346,000,000 |
| April 1962 | 11-6 MR, 15 MA | 4½ years | Approx. 33 mo. | $351,500,000 |
| Actual Prog. | 16-6 MR, 10 MA | 4½ years | Approx. 30 mo. | $384,100,000 |

*MR: Mercury Redstone, MJ-Mercury Jupiter, MA-Mercury Atlas
**Duration of Cape Kennedy Operations is merely the sum of the number of months in which launches were scheduled or conducted. When long breaks in the launch schedule are present, the months in these breaks were not counted

In summary, then, the data used in this study show that Project Mercury costs exceeded the original budget by about $184,000,000 or stated another way, final costs were about 192% of original estimates. This is true even though the program actually carried out contained fewer flights than the program originally scheduled.

## Risk Content of Project Mercury

To evaluate the risk* in a development program before or even after the fact is a difficult undertaking. However, there are data available from which inferences can be drawn as to the risk estimated to be in the program at various times. These data are of three types:

1. Testimonials of knowledgeable people in (and around) the program, given at the beginning of or during the program.;
2. The scope of the planned program as compared to the actual program, i.e., the apparent reserve in the number of flights, for example, that were programmed to meet objectives;
3. The actual occurrence during program life of probabilistic events that specifically influenced time and financial requirements.

### Testimonial Data on Project Mercury

The citations listed below indicate aspects of the risk content of Project Mercury: Mr. Maxime A. Faget, Chief of the Flight Systems Division of the N.A.S.A. Space Task Group, April 9, 1959, stated:

> "The particular type of manned satellite that we have chosen is a ballistic re-entry vehicle....

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* "Risk", as used in this paper, is the extent to which a development program contains possible occurrences which would affect the time and/or money required to achieve specified program objectives. Such probabilistic events are the working or failing of technical approaches that are uncertain at the outset. "Risk" as used here is the uncertainty that flows from a lack of technical and/or programming knowledge.

"The reasons we chose this particular type of vehicle were as follows: Such a vehicle is considerably more compact and lighter than the more sophisticated lifting types of vehicles, and for this reason it was easy to incorporate it with an existing booster system, namely the Atlas....

"This save not only development time and expense, but it also enhances our chance of success inasmuch as we are exploring the unknown with the least amount of new developments in proceeding in this manner."[27]

NASA SP-45

"After the objectives were established for the project, a number of guidelines were established to insure the most expedient and safest approach for attainment of the objectives were followed. The basic guidelines that were established are as follows:

(1) Existing technology and off-the-shelf equipment should be used wherever practical.

(2) The simplest and most reliable approach to design would be followed.

(3) An existing vehicle would be employed to place the spacecraft into orbit.

Basically, the equipment used in the spacecraft was derived from off-the-shelf equipment or through the direct application of existing technology, although some notable exceptions were made in order to improve reliability and flight safety. These exceptions include:

(1) An automatic blood-pressure measuring system for use in flight.

(2) Instruments for sensing the partial pressures of oxygen and carbon dioxide in the oxygen atmosphere of the cabin and suit respectively."[28]

Aviation Week, November 17, 1958, quoting Dr. York of ARPA

"York said it will take a number of years to get the vehicle and capsule system to the point where man can be orbited safely, but he said 'nearly everything we want exists, is about to exist or is solidly under development.'"[29]

Aviation Week, June 22, 1959

> "The technical policy adopted by the task group is to use existing technology and proved methods throughout the Mercury program to save time and money. Although this eliminated the need for new research, it has not been possible to use off-the-shelf equipment and systems in the Mercury capsule."

> "All aspects of the Mercury program rest on firm technical ground. While a great deal of engineering design and environmental test work has yet to be done, the programs have been outlined clearly by the wide experience gained in recent years on the major problems connected with orbital flight."

> "In areas where there is still some doubt about the basic technical approach involved N.A.S.A. has back-up programs."

> "The heat sheild required for the capsule to re-enter the atmosphere is being purchased in both ablation and heat sink forms. While a great deal of nose cone investigation for the ballistic missile program is applicable to the capsule, no re-entry tests ever have been made from an orbit. Orbital re-entry occurs at speeds only slightly higher than intercontinental missile speeds but the energy that must be dissipated as heat or drag is considerably higher and the re-entry paths are different."

> "The Mercury capsule is a less complicated vehicle to develop than a high performance aircraft and its design and test program are expected to move correspondingly faster."[30]

Program Reserve

The program as planned in February 1960 contained the following planned flights: 6 Little Joes, 8 Redstones, and 15 Atlases. The program actually conducted contained: 7 Little Joes. 6 Redstones, and 10 Atlases including the 22 orbit mission.

The planning in February 1960 did not include the 22 orbit missions, so deducting it and the failures (which included 2 Redstones, 2 Atlases and 1 Little Joe) from the actual program, the reserve in planning is found as: 0 Little Joes, 4 Redstones, and 8 Atlases.

In short, a flight test program was planned with about twice as many liquid missiles as would have been required if NASA had not planned for any failures and if the 22 orbit mission had not been planned This infers that NASA expected a failure rate of about .5 for liquid missile boosted flights.

In summary, it appears from available data that the Mercury capsule development was thought to be straightforward except for a few areas such as the heat shield. Whenever the success of the outcome was in doubt, back-up programs were utilized to reduce this risk to low levels. In the case of the heat shield, little doubt remained by February 1960 (when the "15 Atlas" program was laid out), since the Big Joe shot of mid-1959 had removed this doubt.

The tracking network, though underestimated as to cost, was not thought to be risky in a technical sense. It checked out the first time it was tested and "performed beyond our expectation".[31] One can at least speculate that at the $53.0 million it finally cost for procurement and installation little risk was present in the program.

The major risk area then appears to be system reliability--uncertainty that the missions could be flown in the minimum number of flights. The probability of success used for planning of a liquid missile boosted flight appears to be about .5.

## ANALYSES OF PROJECT MERCURY

Project Mercury achieved the desired technological results but it incurred both financial and time overruns. Based on data in this paper, the cost overrun of the initial program budget was 184 million dollars and the time overrun for the program was about 30 months. Put in the language of previous studies of this sort, the time slippage factor was 2.25 and the

budget overrun factor was 1.92. If one estimates these factors based on the flight of MA-6 (1st manned orbital flight, which might be used to mark the end of the development program), they are respectively about 2.2 and 1.93. An earlier section of this paper presents a gross reconciliation of schedule slippage. To what causes can the budget overruns be attributed? At least four general causes are apparent:

1. Accumulation of overhead costs due to time slippage;
2. Growth in the tracking network costs[32];
3. Flight failures causing increased direct costs;
4. Purchase of additional equipment over that thought to be required when the initial budget was layed out.

Crude analyses of actual financial data from the program permit the following highly approximate cost attributions:

| | $ x millions |
|---|---|
| Overhead accumulation due to time slippage | 106.0 |
| Growth in tracking network costs | 44.5 |
| Flight failures | 20.7 |
| Purchase of additional equipment | 20.9 |
| | 192.1 |

The assumptions and methods used to calculate these attributions are presented in Appendix 1 of this paper.

Proceeding along these lines a very rough measure of the minimum financial uncertainty in Project Mercury is apparent. The actual cost of the project was $384.1 million. The four classes of "events" described above, each probabilistic in nature or growing out of probabilistic considerations, accounts for $192.1 million. This implies that the minimum the program could have cost was in the neighborhood of $190.0 million.

NASA programmed and bought 5 Atlas boosters that were not ultimately required and 2 Redstones, with spacecraft for all of these. Consequently additional launches required only operational costs. Incremental costs of one Atlas launch and one Redstone launch (excluding costs of hardware) were estimated at 12.0 and $8.7 million respectively. If failures had occurred requiring the use of all the hardware on hand, somewhere in the neighborhood of $77.0 million more would have been required therefore for a total program cost of about $460 million, or a range of $270.0 million dollars. One might think of these figures as representing a probability distribution. A plausible (though not necessary) assumption is that such a distribution is nearly normal, since it is made up of a large number of other distributions and the working of the central limit theorem might lead to such normality.

The range of uncertainty of $270.0 million arrived at above is a little surprising when one reconsiders the evident lack of technological uncertainty in the program. This reconsideration leads logically to the next element of analysis. What aspects of the Mercury program process contributed to the total financial uncertainty (as contrasted to that part identified above) that existed in the program?

## Lack of Definition at the Inception of the Program

A lack of definition appears to have existed specifically in the tracking network and is alluded to in testimony of Mr. T. Keith Glennan, former Administrator of NASA, before the Authorization Subcommittee of the Senate Committee on Aeronautical and Space Science in March of 1960.[33] This lack also manifests itself in the need to procure substantial additional qualities of hardware after the first budget was established. This additional equipment was referred to also by Dr. Glennan in the testimony of footnote 33.

## Primary Concern for Astronaut Safety

A general and no doubt necessary tendency to decide nearly all trade-offs with astronaut safety as the paramount criterion also contributed to the uncertainty. The following quotations from NASA's Summary Report on Project Mercury illustrate this policy:

In a discussion of reliability and flight safety the following statement is made:

> "Consideration of cost, manpower, or schedule were never allowed to influence any decisions involving mission success or flight safety."[34]

> "Basic equipment designs and implementation criteria for this program (the tracking network) were the result of several major considerations. One of them was economics: existing facilities were to be used whereever they met the Mercury location requirements. Thus at six locations a major part of the equipment, including most of the network's tracking radars, was already available. Another major consideration was time. Maximum use of existing, proven equipment was dictated by the necessity to avoid the long hard times required for research and development. But the primary consideration, over-riding all others, was the safety of the astronaut."[35]

The primary effect of this safety consciousness was probably to increase the time required to complete specific tasks through increased attention to test details and through an increased readiness to accept changes to the system promoted on the grounds of safety. Both of these, increased time and system changes, of course acted to increase costs of the program.

## Systems Engineering Problems

Further accentuating the effect noted above is probably a deficient system engineering job on the space capsule itself. The comparative results on the two major integration tasks are striking and lend support to such a view.

Among the causes for delay at Cape Kennedy, NASA, in SP-45, pointed out that the average time taken for spacecraft modifications was 3½ months; 1 1/3 months were used for actual hangar testing, and 1 month while the spacecraft was on the launch pad. These long preparation times were partially accounted for by inadequate test provisions in the spacecraft, the difficulty of access to various installed systems, etc.[36] Also the unavailability of documented test procedures, the wearing out or life expiration of equipment and lack of space were cited.[37] (See NASA SP-45 Chapter 14, for a detailed review of these problems.)

One can also cite the structural failure in the flight of MA-1 as a system integration deficiency that was found only in test. It is interesting to speculate here inasmuch as the "Big Joe" flight which preceeded MA-1 had an Atlas booster with "thick skin" and no failure occurred. MA-1 was a "thin skinned" Atlas and failure did occur.[38] The fix was to thicken the skin on MA-3 (with an interim fix on MA-2) to about that thickness used in the Big Joe Flight.[39] The question arises: Where were Mercury systems engineers when the decision was made to reduce skin thickness on MA-1? The point here, obviously, is not to cast a stone but to highlight what appears to be a different level of performance in the spacecraft—booster system engineering and system integration areas and that (to be discussed below) in the tracking network.

As was pointed out early in this paper the tracking network too, presented a system engineering and integration challenge. Chapter 8 of SP-45 covers the development and performance of this network in great detail. Among the points worthy of note are the following:

1. By May of 1961 the network was fully operational and training had been conducted at all sites.[40]

2. Manuals of various types were provided for the network users.[41]

3. Self test capabilities were built into the network[42]

4. Logistic support was provided for in advance and spares did not present the problems presented by the spacecraft.[43]

One is forced by these two examples to a tentative conclusion that for some reasons, a different quality job of systems engineering and integration was done on these two major elements of the Mercury system. Underlying this difference would appear to be several significant process elements.

Schedule. The spacecraft was developed on an extremely tight schedule. For example, the contract for the spacecraft was signed in January 1959. The mockup of the spacecraft was inspected only 2 months later in March. The first complete spacecraft was delivered in March of 1960, only about 14 months after contract signing.[44] Allowing 9 or 10 months for manufacturing lead time (a very short period for a first article of this nature) only 4 or 5 months are left for design. Granting that design began upon receipt of the request for proposal, only some 6 or 7 months were spent on design. Following the first spacecraft delivery, on the average, about one per month was delivered for the next year.

The world wide tracking network on the other hand was placed on contract in July 1959. Prototype tests were conducted at Wallops Island in July 1960 and operational status was achieved in March 1961.[45] Recalling that most of the tracking network was standard equipment and that the Wallops Island tests were of a prototype installation, it is clear that this simpler task was conducted on a more leisurely schedule.

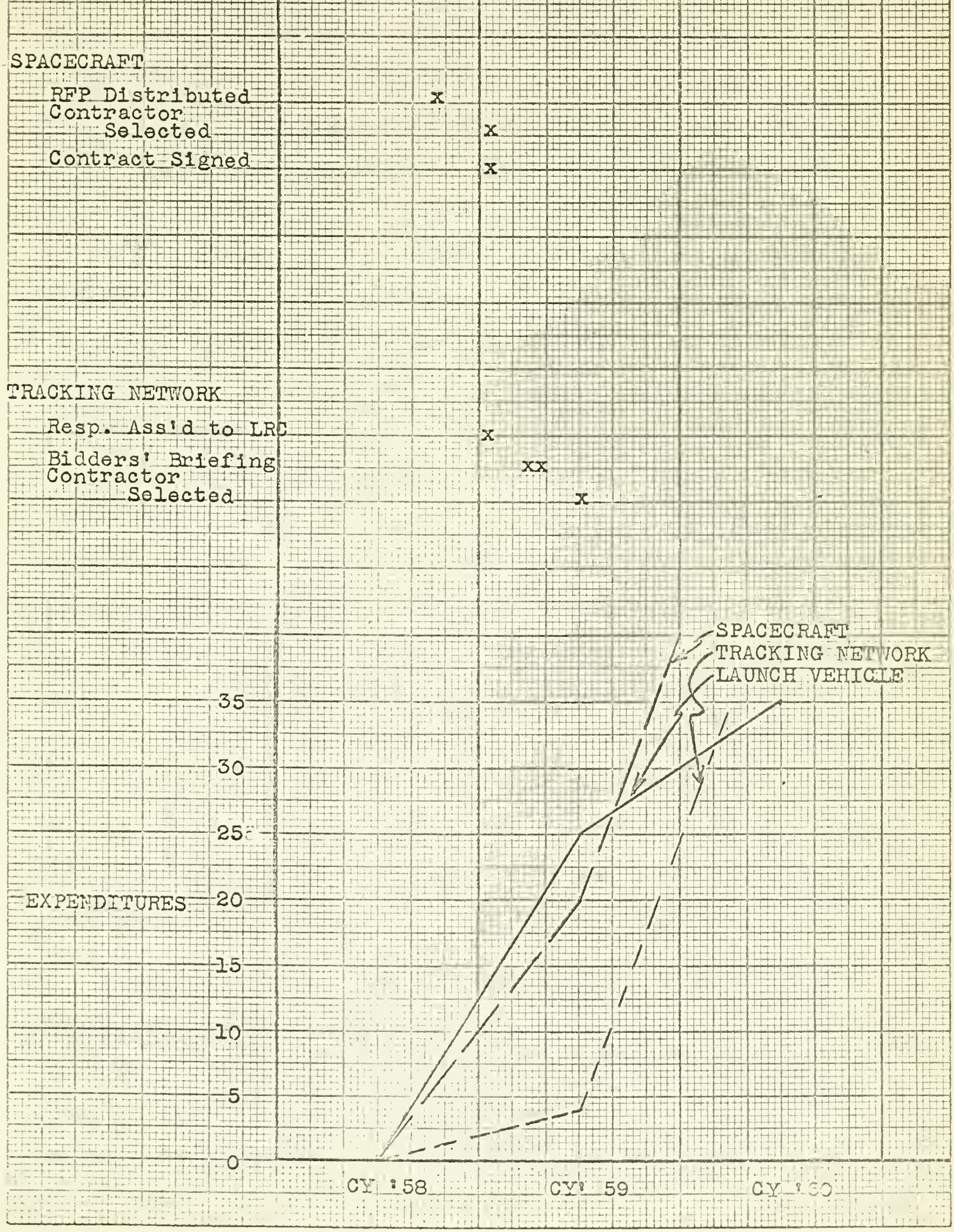
Another factor in the schedule situation is the competition that was possibly felt in Mercury prior to the first orbital flight by the Soviet Union.

Examination of Figure 3 shows a sharp break in the rate of the achieved program schedule in about April or May of 1961. The Gagarin flight of course occurred on April 12, 1961 and our own manned program began on May 5, 1961. Prior to this time, though discrete slippages had occurred, rates of accomplishment generally were about equal to those planned. After this time rate of achievement fell sharply from that originally planned. Obviously, our program had entered the operational phase, become more complex, and the operations had become more critical. But a logical question remains of the influence of the Gagarin flight in removing some of the urgency from the Mercury Project.

Some evidence is present that indicates that the airborne elements of the system were in a race but that the tracking network was not. Such an approach fits a "race with the Russians" theory if we were willing to "win" the race with a Redstone flight. The range of Redstone was only about 250 miles and it is quite clear that the tracking network except for the Cape Kennedy installation was not required for such a flight. Examination of tracking network schedules clearly show that Cape Kennedy installation including the Mercury Control Center was programmed to be available (provisionally accepted) substantially earlier than most of the other stations--1 station was three months later, 3 stations were four months later one, five months later, and the remainder more than five months later.[46]

Also, examination of the tracking network's actual procurement schedule and the expenditure rate in early 1959 forces one to the conclusion that even at this early date the tracking network was on a different schedule than that of the spacecraft. Figure 5 shows these schedules and accumulated expenditures on the spacecraft and the tracking network. The launch vehicle expenditures are also shown. The point here is simply that the network was about 6 months

FIGURE 5
Schedules and Expenditures versus Time for Initial Phases of Spacecraft, Launch Vehicle, and Tracking Network Development



slower than the spacecraft even getting into development. The implication of this is that by early 1959, orbital flights were not in fact expected prior to early 1961. Yet at this time the first orbital flight was scheduled for April 1960.[48] One other possibility of course is that the first orbital flight would have been made without a world wide tracking network; however, the emphasis on safety tends to rule out such a plan.

In summary, then, there is evidence that for any or all of several possible reasons the spacecraft development was scheduled very tightly whereas the tracking network was on a looser schedule. This no doubt contributed significantly to the apparent quality difference in the system engineering of the two systems.

Heterogeneity of Technologies. It is reasonably clear that the spacecraft with its aerodynamic, structural, electronic, aerothermodynamic, mechanical, thermodynamic, human factor, environmental, manufacturing, and probably other technological requirements presented more complex engineering and management problems than did the network with its narrower range of technological needs. The problems associated with optimal design of systems employing such ranges of technological skills constitute the meat of the systems engineering and integration task. Achieving adequate communication among the specialists in these technologies and the breaking down of parochial interests takes time. The time allowed was probably inadequate in the complex case of the spacecraft and adequate in the less difficult case of the tracking network.

Organization. There is some evidence, though it is admittedly weak in available public references, that the spacecraft was largely system engineered by the Space Task Group, a new NASA group formed especially for Mercury. The tracking network on the other hand was assigned to an established operation at Langley Research Center. If such is in fact true, this could have been

an influencing factor. Such a factor would logically be accentuated since many system engineering decisions must be made early in a program just at the time a new group is most likely to be inefficient and ineffective.

Development Results in Mercury Related to other Development Projects

The best available body of data to which the results of the Mercury project can be related is contained in Peck and Scherer's The Weapons Acquisition Process: An Economic Analysis. Tables 2.1 and 10.1 of that book are combined and reproduced as Table 4 of this paper.[49] Added to this table are Mercury results. The values entered were arrived at in the following ways:

Exploitation of the State of the Art. Based on data in this paper Mercury was estimated to be less exploitative than a higher performance aircraft. Three such aircraft are the sample of Table 4. These aircraft are the B-58, F-4H and the F-105. Mercury was estimated to be less exploitative than any of these, an "exploitative" value of 50 was therefore used for Mercury.

Importance of Development Time. Mercury was estimated to be as urgent as the most urgent project prior to April 1961. Subsequent to that time urgency was assumed to have dropped by ½. This yields an average value for the program of 75.

Importance of Development Cost. Mercury was estimated to be about the same as the highest priority missiles which ranged from 0 to 40. An average of these two values was chosen.

Relative Technical Difficulty. A value was chosen equal to the lesser of the aircraft projects.

Development Cost Factor. All costs to MA-6 were included and divided by $160.0 million. This yields a value of 1.93. The $160.0 million figure results from reducing the $200.0 million original budget in proportion to

TABLE 4

| Project | Class* | Exploitation of State of the Art | Importance of Division Time | Importance of Development Cost | Relation Technical Difficulty | Development Cost Factor | Development Time Factor |
|---|---|---|---|---|---|---|---|
| A | GM | 95 | 70 | 25 | 90 | 4.0 | 1.0 |
| B | GH | 65 | 40 | 40 | 50 | 3.5 | 2.3 |
| C | GM | 92.5 | 25 | 30 | 80 | 5.0 | 1.9 |
| D | GM | 55 | 80 | 20 | 30 | 2.0 | n.a. |
| E | GM | 95 | 100 | 0 | 95 | n.a. | .7 |
| F | GM | 90 | 50 | 40 | 85 | 7.0 | 1.8 |
| G | GM | 80 | 90 | 10 | 70 | 3.0 | 1.3 |
| H | GM | 50 | 90 | 40 | 40 | 2.0 | 1.0 |
| I | A/C | 85 | 60 | 40 | 85 | 2.4 | 1.3 |
| J | A/C | 60 | 75 | 50 | 60 | 2.5 | 1.3 |
| K | GM | 80 | 95 | 10 | 80 | .7 | 1.0 |
| L | A/C | 60 | 50 | 50 | 60 | 3.0 | 1.4 |
| Mercury | S/C | 50 | 75 | 20 | 60 | 1.93 | 2.2 |

GM--Guided Missile

A/C--Aircraft

S/C--Spacecraft

the reduction in the \$384.1 million budget due to exclusion of the part of the program beyond MA-6.

Development Time Factor. Time to MA-6 was used divided by 19 months, the original period allowed until the first manned orbital flight - $\frac{19+22}{19} = 2.2$

Inspection of this table immediately reveals a difference between projects A through L and Mercury in that the development-cost factor in almost every case substantially exceeds the development time factor. In Mercury, however, the reverse is true.

Other relationships can best be looked at by examination of figures 6 through 12 below:

Correlation of Time Slippage Factors with State of the Art Exploitation

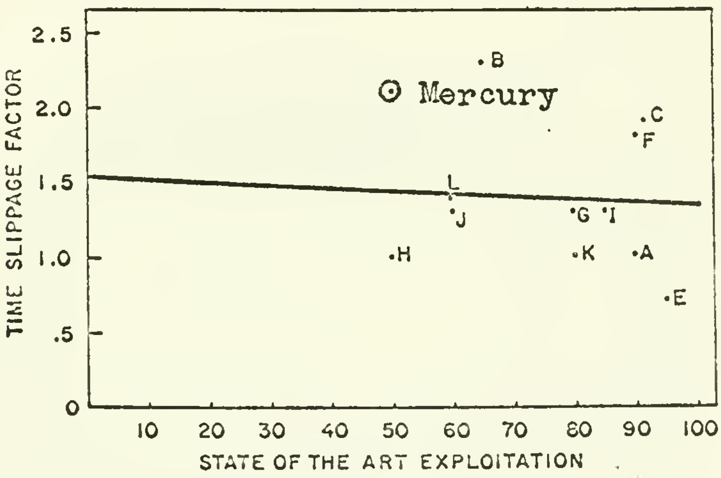



FIGURE 6

Correlation of Cost Overrun Factors with
State of the Art Exploitation

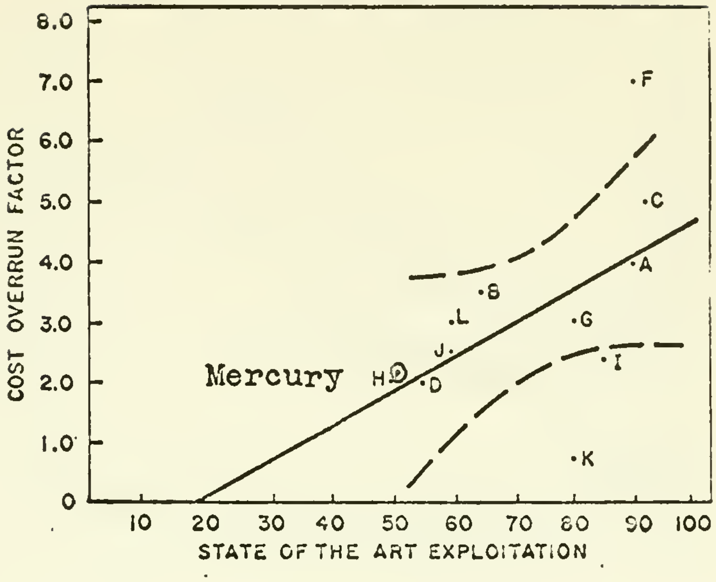



FIGURE 7

Correlation of Cost Overrun Factors with
the Importance of Minimizing Cost

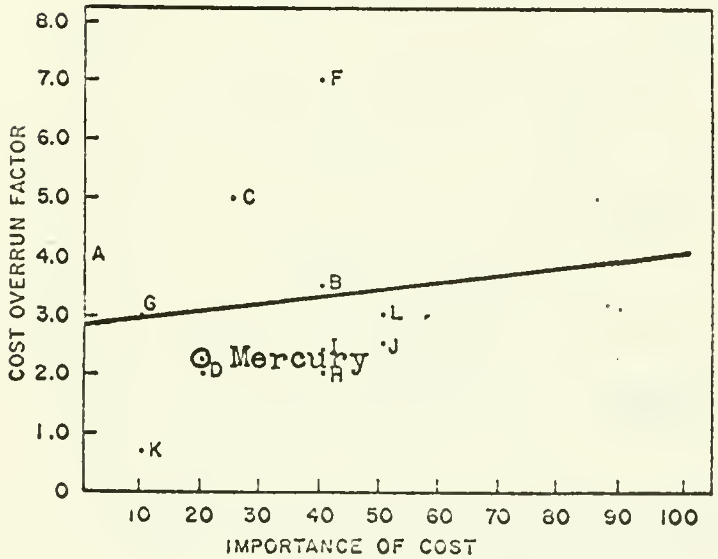



FIGURE 8

Correlation of Cost Overrun Factors with the Importance of Minimizing Time

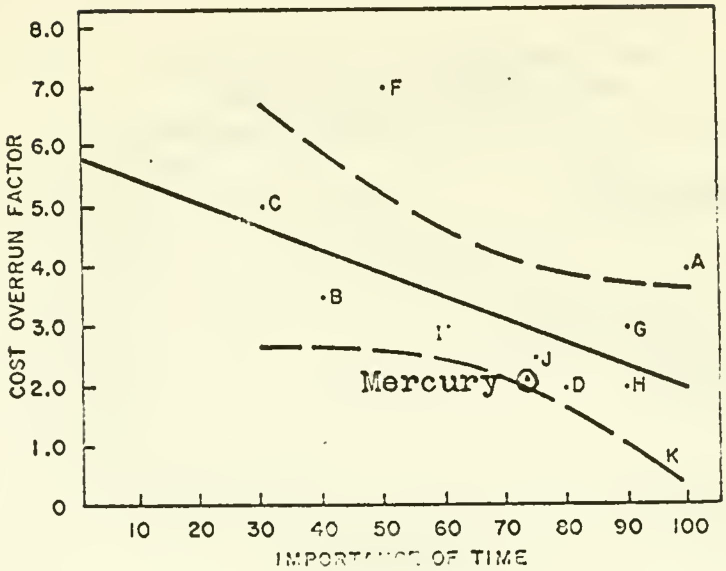



FIGURE 9

Correlation of Cost Overrun Factors with Time Slippage Factors

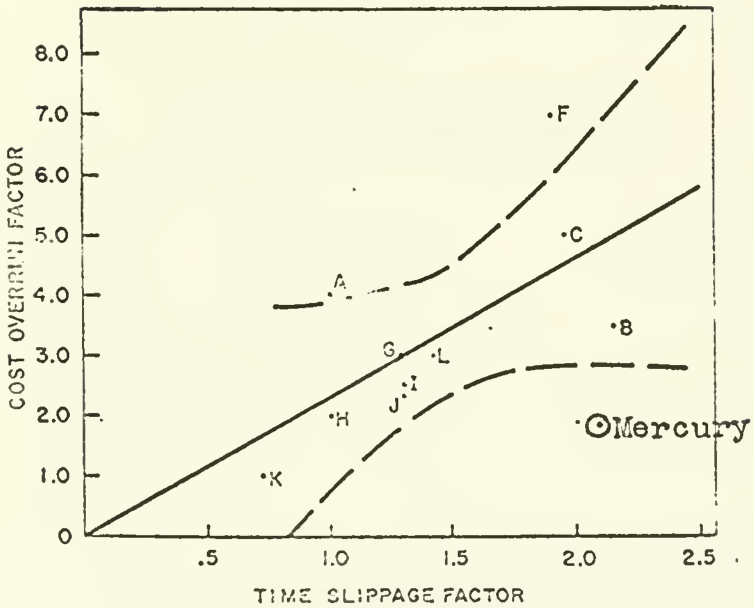



FIGURE 10

Correlation of Time Slippage Factors with
the Importance of Minimizing Time

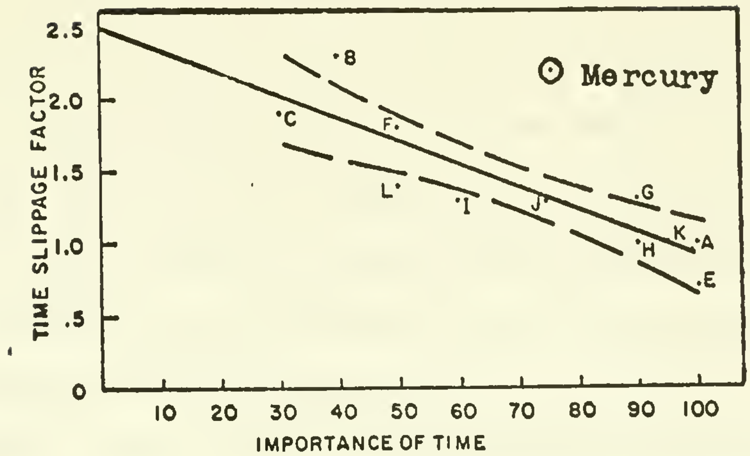



FIGURE 11

Correlation of Time Slippage Factors with
the Importance of Minimizing Cost

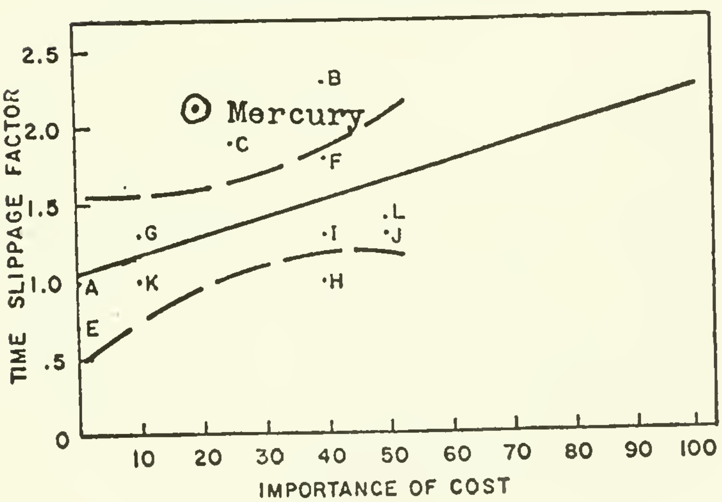



FIGURE 12

These figures show that Mercury experienced more time overrun than would have been predicted from the projects A through L, given Mercury's cost overrun factor and the other indices used. This can be explained a number of ways. Probably the most credible is that the time slippage resulted from safety considerations and related problems discussed elsewhere in this paper, and that this slippage occurred in the main at a time in the program, during flight test, when overhead bases had diminished. The program stretchout then was less costly than it would have been had it occurred during an earlier phase of work.

In summary, then, Project Mercury experienced project results generally consistent with other similar programs except that time overrun was greater per unit of financial overrun.

## Appendix 1 Financial Analysis

1. Overhead Calculations:

| | |
|---|---|
| Total actual cost of program | \$384.1 million |
| Total duration of the program | 54 months |
| Average expenditure rate | $\frac{384.1}{54}$ = \$7.1 million/mo. |

Assumption: Overhead rate is 100% of direct effort. Average overhead expenditure rate then was \$3.55 million/mo. This assumption is based on the author's experience with numerous similar situations. In general, overhead rates range from about 90% to 135% depending on factors such as which contractors are involved, whether the rate is to be applied to engineering or manufacturing, etc.

$$30 \text{ months} \times \$3.55 \times 10^6 = \$106.0 \times 10^6$$

2. Growth in tracking network costs:

Original estimate = \$35.0 million[57]

Final cost = \$124.0 million[38]

Total difference = \$89.0 million

Total direct cost addition = \$44.5 million (based on 100% overhead assumption above)

3. Flight failures:

Incremental costs of 1 Atlas flight = \$12.0 million[59]

Assumption: Costs above were attributable to launch operations and time passage, not to hardware. This assumption is based on the fact that ample hardware existed in the program to support the extra launches.

Assumption: Cost of a Redstone launch = $\frac{117}{160}$ x \$12 million = \$8.7 million.[60]

This assumption is based on costs being proportional to launch preparation time. Then direct costs, using 100% overhead, of 2 Atlas and 2 Redstone failures = \$20.7 million.

4. Purchase of additional equipment:

5 Atlas boosters

at a direct cost of \$2.29 x $10^6$* each = \$11.4 x $10^6$ [61]

12 spacecraft

at a direct cost of \$ .79 x $10^6$** each = \$9.5 x $10^6$ [62]

\$20.9 x $10^6$

5 Total cost of 1 through 4.

| | |
|---|---|
| \$106.0 x $10^6$ | Overhead due to schedule slippage |
| 44.5 x $10^6$ | Growth in tracking network costs (direct costs) |
| 20.7 x $10^6$ | Costs attributable to flight failures (direct costs) |
| 20.9 x $10^6$ | For purchase of additional equipment (direct costs) |
| \$192.1 x $10^6$ | |

---

* \$2.29 x $10^6$ derived by taking total launch vehicle cost from NASA SP-45, removing Redstone costs and Little Joe costs, based on estimates in Project Mercury, a Chronology, dividing by 15 (for 15 boosters) and applying an assumption of 100% overhead.

** \$.79 x $10^6$ derived by taking total spacecraft manufacturing cost from SP-45, adding to this a proportional part of subcontracting, dividing by 24 (for 24 spacecraft) applying the 100% overhead assumption.

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